Structure of exotic nuclei near and above ^{208}Pb populated via deep-inelastic collisions

G.J. Lane[a], R. Broda[b], B. Fornal[b], A.P. Byrne[c,d], G.D. Dracoulis[c], J. Blomqvist[e], R.M. Clark[a], M. Cromaz[a], M.A. Deleplanque[a], R.M. Diamond[a], P. Fallon[a], R.V.F. Janssens[f], I.Y. Lee[a], A.O. Macchiavelli[a], K.H. Maier[b,g], M. Rejmund[h], F.S. Stephens[a], C.E. Svensson[a], K. Vetter[a], D. Ward[a], I. Wiedenhöver[f], and J. Wrzesinski[b]

[a]Lawrence Berkeley National Laboratory, U.S.A.

[b]Niewodniczański Institute of Nuclear Physics, Poland

[c]Department of Nuclear Physics, Australian National University, Australia

[d]Department of Physics, Australian National University, Australia

[e]Royal Institute of Technology, Sweden

[f]Argonne National Laboratory, U.S.A.

[g]Hahn-Meitner Institute, Germany

[h]CSNSM, Orsay, France

High-spin states have been studied in neutron-rich nuclei produced in deep-inelastic collisions between a pulsed beam of ^{208}Pb ions and a ^{238}U target. The structure of nuclei such as ^{206}Hg, ^{210}Pb and ^{211}Bi has revealed new information on the couplings of single-particle states to each other and to the octupole-vibrational phonon, essential input to the nuclear shell model. In addition, the first observations of high-spin states in ^{237}U, ^{239}U and ^{240}U are compared to recent results for neighbouring plutonium nuclei.

1. INTRODUCTION AND EXPERIMENTAL METHODS

Nuclei around the doubly-closed shell at ^{208}Pb have long been of interest both with regard to the shell-model behaviour of states in nuclei in the region and because of the presence, and coupling, of collective excitations to these states and the subsequent evolution of collective behaviour (in particular octupole collectivity) as one moves away from the closed shell. However, many of the important neutron-rich nuclei cannot be populated by conventional (HI,xn) reactions, so that other methods must be employed. Information on the decay of isomeric states in nuclei such as ^{211}Bi and ^{212}Pb has been obtained from relativistic fragmentation of heavy beams [1], but currently only deep-inelastic reactions provide the opportunity to perform prompt γ-ray spectroscopy on these neutron-rich nu-

clei. So far, deep-inelastic collisions have been employed to study nuclei near ^{208}Pb using beams with $A \leq 208$ on ^{208}Pb targets (see, for example, Refs. [2–4]).

We performed an experiment at Argonne National Laboratory to study excited states in neutron-rich isotopes populated by deep-inelastic collisions between a pulsed beam (1.6μs separation) of ^{208}Pb ions from the ATLAS accelerator and a 50 mg/cm^2 ^{238}U target. The beam-target combination was chosen to preferentially populate the more neutron-rich nuclei above ^{208}Pb. The target was thick enough to stop both beam-like and target-like recoils within $\sim$ 2 ps. The γ-rays emitted from nuclei at rest were observed with Gammasphere consisting of 101 Compton-suppressed detectors. A composite trigger was used for the in-beam events (3 or more suppressed γ-rays in coincidence) and out-of-beam events (2 or more suppressed γ-rays in coincidence). Approximately 2.3×10^9 events were collected in total, of which 1.1×10^9 were fold 3 or greater.

Coulomb excitation of the ^{238}U target nuclei caused a significant γ-ray background which was especially problematic because of the large Doppler-broadened component of the higher energy lines. Fortunately the γ-rays from ^{238}U are mostly limited to the region below $\sim$ 600 keV so that the coincidence spectra for high-energy γ-rays emitted from the products of deep-inelastic collisions are generally free of this background. In addition, the timing information enables the separation of the mostly prompt ^{238}U γ-rays from the delayed γ-rays which are due to the decay of isomeric states in the many shell-model nuclei populated around ^{208}Pb. Gating on these delayed γ-rays provides a very sensitive method of extracting weakly-populated prompt γ-ray cascades from the intense background of Coulomb-excitation γ-rays.

The analysis has been greatly facilitated using the code Blue [5]. The entire dataset, including the γ-ray energies, times and angles of detection, are stored in an indexed, energy-ordered database on computer disk. Blue provides an environment for the interactive creation of matrices (in less than 5 minutes) gated by complicated combinations of gates on the γ-ray energies, absolute times and relative time differences between γ rays. Rapid optimisation of the gating requirements enables clean matrices to be quickly created for very weak channels as they are identified.

2. TWO PROTON HOLE NUCLEUS: ^{206}Hg

Prior to the present work only two excited states were known in the two-proton hole nucleus ^{206}Hg, the 2^+ state and a 5^- isomeric state with $T_{1/2}$=2.15 μs from the $\pi h_{11/2}^{-1} s_{1/2}^{-1}$ configuration. A low-lying isomeric state with the $[\pi h_{11/2}^{-2}]_{10+}$ configuration is expected.

A matrix was created of all pairs of γ-rays which precede in time either of the known 1034 and 1068 keV γ-rays from the cascade below the 5^- isomer. The projection of this matrix is shown in Fig 1a. Some γ-rays are present from the ^{238}U ground-state band due to random coincidences, however the marked γ-rays can clearly be correlated with the decay of states which feed the known 5^- isomer in ^{206}Hg. The summed time spectra with respect to the beam pulse for the 364, 1157 and 1257 keV γ-rays is shown in the inset to Fig 1a and confirms the presence of a new isomer with $T_{1/2}$=90(10) ns. Transitions above this isomer were further enhanced in a new matrix of pairs of γ-rays which precede these three transitions.

The preliminary level scheme for ^{206}Hg is shown in Fig 2. The new isomer is almost
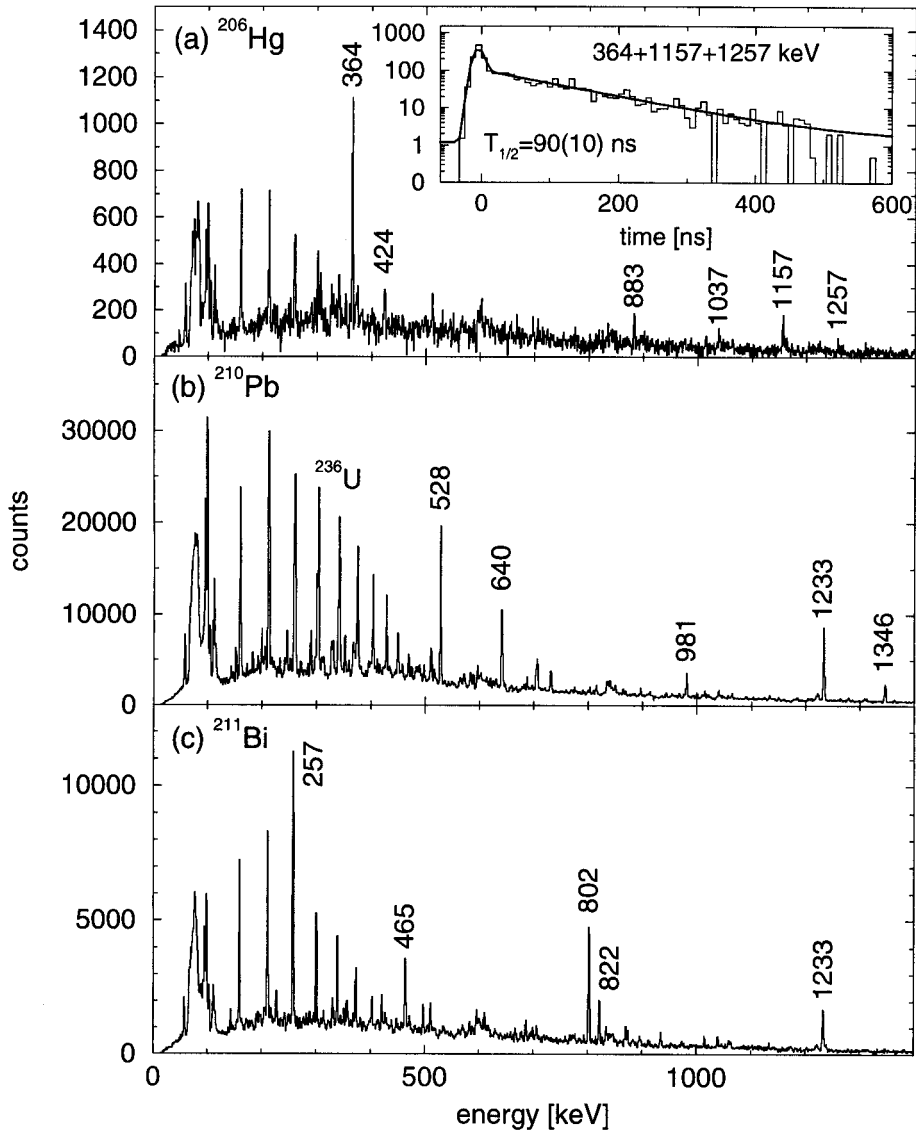
Figure 1. Projections of matrices gated on transitions below previously known isomers in (a) ^{206}Hg, (b) ^{210}Pb and (c) ^{211}Bi. All three γ-ray spectra have "random" γ-rays present from the ground-state band in ^{238}U. The inset in (a) is the time spectrum with respect to the beam pulse for the three marked transitions from ^{206}Hg.
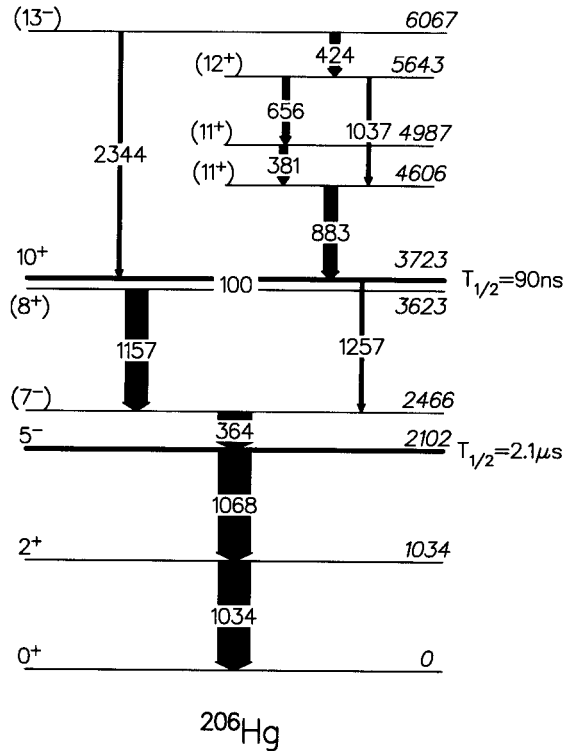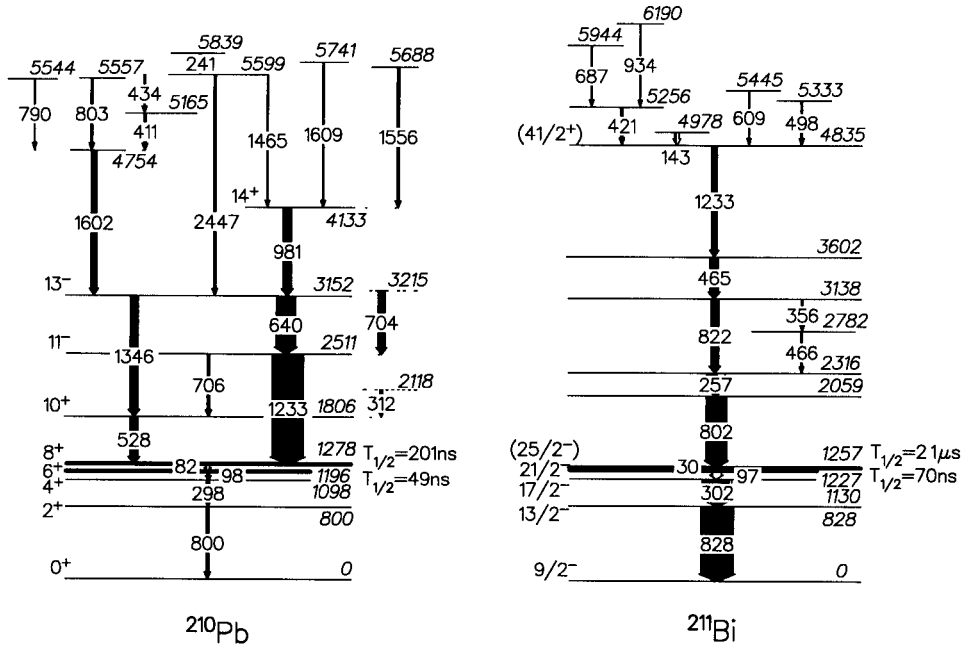
Figure 2. Preliminary level scheme for ^{206}Hg.

certainly the expected 10^+ state corresponding to the maximum spin coupling of two $h_{11/2}$ proton holes. The 8^+ state is also due to the $\pi h_{11/2}^{-2}$ configuration so that the 10^+ isomeric lifetime can be used to deduce the effective charge for the $\pi h_{11/2}$ proton hole, $e = 1.60(7)$. This value can be compared with the value $e = 1.52(5)$ deduced for the $\pi h_{11/2}$ proton particle at the other end of the major shell (from the 10^+ isomer in ^{148}Dy [6]).

The 13^- state results from the coupling of the 3^- octupole phonon to the 10^+ state. The coupling of the 3^- octupole phonon to various single-particle states in nuclei around ^{208}Pb has been examined recently [7]. Particle-vibration calculations like those in Ref. [7] which use as input the measured energy of the octupole $(\pi h_{11/2}^{-1} \otimes 3^-) \rightarrow \pi h_{11/2}^{-1}$ transition in ^{207}Tl can accurately reproduce the observed energy in ^{206}Hg

The 7^- and 8^+ states at 2466 and 3623 keV are due to the $\pi h_{11/2}^{-1} d_{3/2}^{-1}$ and $\pi h_{11/2}^{-2}$ proton hole configurations These, plus the 10^+ isomeric state, define values for the two proton-hole empirical interactions from the $[\pi h_{11/2}^{-2}]_{10^+}$, $[\pi h_{11/2}^{-2}]_{8^+}$ and $[\pi h_{11/2}^{-1} d_{3/2}^{-1}]_{7^-}$ states to be 409, 309 and 142 keV, respectively. These results are in good agreement with the theoretical calculations of Kuo and Herling [8], 360, 320 and 60 keV, respectively

The states between 4 6 and 5 7 MeV are most likely due to neutron core-excitations

Figure 3 Preliminary level schemes for (a) ^{210}Pb and (b) ^{211}Bi

3. N = 128 NUCLEI: ^{210}Pb AND ^{211}Bi

The nucleus ^{210}Pb has been studied previously using deep-inelastic collisions in Ref. [4] In that work, the excited states up to the maximum spin possible from the two valence neutrons ($[\nu j_{15/2}^2]_{14+}$ state at 4133 keV) were identified by projecting a matrix of pairs of γ-rays which precede the known 6^+ and 8^+ isomers. A similar procedure for the present data yields a matrix with 50 times more counts in the projection (compare Fig. 1b with Fig. 1 in Ref. [4]) Accordingly, the preliminary level scheme deduced from the present experiment for ^{210}Pb and shown in Fig. 3a is more extensive than the previous work. It is clear that the new states at an excitation energy of 4754 keV and higher must be due to core-excitations Calculations attempting to understand the structure of these states are in progress

The nucleus ^{210}Bi is the ideal laboratory for studying the proton-neutron single-particle couplings which are important around ^{208}Pb. However, the low-lying $[\pi h_{9/2} \nu g_{9/2}]_{9-}$ $T_{1/2} = 3 04 \times 10^6$ year isomer makes it impossible to identify high-spin states via coincidence spectroscopy across the isomer Another possible approach is to look at high-spin states in ^{211}Bi from which the proton-neutron couplings can be extracted with relative simplicity. Note also, that ^{211}Bi can be naively considered as the coupling of a proton to the ^{210}Pb nucleus discussed above

Before the present work only a few low-lying states due to the $\pi h_{9/2} \nu g_{9/2}^2$ configura-

tion were known in ^{211}Bi. The states up to the $[\pi h_{9/2}\nu g_{9/2}^2]_{21/2-}$ isomeric level (with $T_{1/2} = 70$ ns) at 1227 keV were identified using γ-ray spectroscopy [9], while a tentative spin assignment of $(25/2^-)$ corresponding to the $[\pi h_{9/2}\nu g_{9/2}^2]_{25/2-}$ configuration was made to a level at 1257(10) keV observed via charged-particle spectroscopy [10]. A long-lived $T_{1/2} = 2.1$ μs isomer was observed in the relativistic fragmentation experiment of Pfützner *et al.* [1] but this lifetime could not be positively associated with either the known $[\pi h_{9/2}\nu g_{9/2}^2]_{25/2-}$ state or a predicted $[\pi h_{9/2}\nu g_{9/2}i_{11/2}]_{29/2-}$ state.

The projection of a matrix containing all pairs of γ-rays which precede in time either of the known 828 and 302 keV transitions which decay from the $13/2^-$ and $17/2^-$ states is shown in Fig. 1c. The marked lines are associated with the decay of states above one or more of the (possibly unidentified) isomers in ^{211}Bi. The coincidence properties of the new lines have allowed the tentative level scheme shown in Fig. 3b to be constructed. (It is assumed that the cascade feeds the known state at 1257(10) keV.)

The fragmentation of the decay scheme above the 4835 keV state is similar to ^{210}Pb and is highly suggestive (but not conclusive) that this state corresponds to the maximum spin available from the three valence nucleons, that is the $[\pi i_{13/2}\nu j_{15/2}^2]_{41/2+}$ configuration. Empirical shell model calculations using two-body interactions predict this state at 4856 keV, in close agreement, although other core-excited states are also calculated at similar excitation energies. Despite this agreement, an understanding of the observed states is not straightforward at this time. In particular, there is a question as to whether the observed cascade feeds the known $[\pi h_{9/2}\nu g_{9/2}^2]_{25/2-}$ state or perhaps the expected $[\pi h_{9/2}\nu g_{9/2}i_{11/2}]_{29/2-}$ state. These states are calculated to lie within 10 keV of each other when using the value for the $[\pi h_{9/2}\nu i_{11/2}]_{10-}$ empirical interaction of -778 keV deduced from the 10^- state in ^{210}Bi. It is thus possible that the $29/2^-$ state could even fall below the $25/2^-$ state in which case it could β- or α-decay so that the γ-ray cascade selected by gating on the low-lying γ-rays might not correspond to the yrast cascade. It is interesting to note however, that the experimental $[\pi h_{9/2}\nu i_{11/2}]_{10-}$ interaction deduced from ^{210}Bi is 300 keV more attractive than the Kuo-Herling prediction of -480 keV [8]. If the actual value were more in line with the Kuo-Herling prediction, the calculated yrast line will change significantly, with the $29/2^-$ state lying 300 keV higher. It is noteworthy that even this simple system of three valence particles provides an experimental and theoretical challenge, highlighting the importance of studies of nuclei in this region.

4. HIGH-SPIN STATES IN ^{237}U, ^{239}U AND ^{240}U

The thick-target Coulomb-excitation experiments pioneered by Ward *et al.* [11] demonstrated a new experimental method with which to study high-spin states in actinide nuclei. High-spin states in plutonium nuclei from $A = 238$ to $A = 244$ were subsequently studied by Wiedenhöver *et al.* using single-neutron transfer and Coulomb-excitation reactions with ^{208}Pb and ^{207}Pb beams incident on various plutonium targets [12]. Their results appear to show the unexpected onset of strong octupole correlations at high spin in the plutonium nuclei with $A \leq 240$. No high-spin states are known in some of the neighbouring uranium nuclei, with only fragmentary states up to $\sim 15/2$ $\hbar$ known in ^{237}U and ^{239}U, while only the 2^+ state is known in ^{240}U. In view of the plutonium results it is important to study these uranium neighbours at high spin.
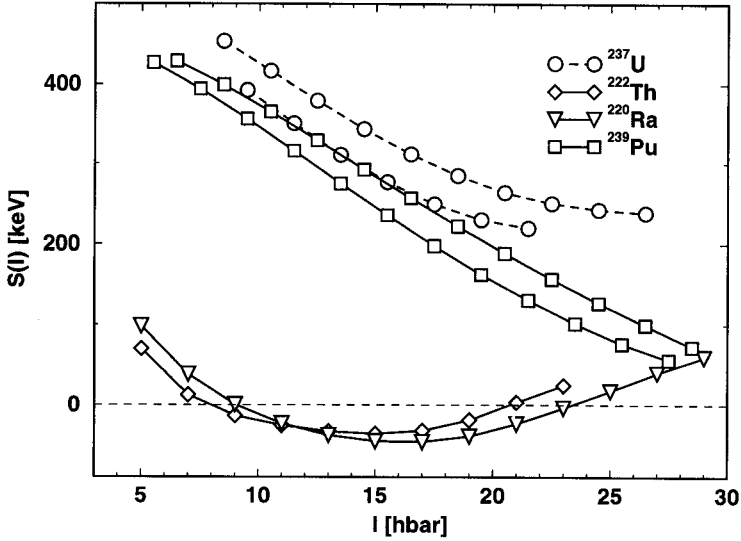
Figure 4. Energy splitting between positive- and negative-parity sequences in various actinide nuclei.

These nuclei were populated by one and two-neutron transfer processes in the present experiment. Assignment of γ-rays to the appropriate uranium nuclei was clear from cross-coincidences with the complementary lead fragments. The ground-state band has been observed up to $28\hbar$ in ^{240}U. Three bands based on the $1/2^+[631]$, $5/2^+[622]$ and $7/2^-[743]$ Nilsson states have been observed up to spins of $57/2\ \hbar$ in ^{239}U, while in ^{237}U the rotational bands based upon the $1/2^+[631]$ and $7/2^-[743]$ Nilsson states have been identified. In addition, the octupole side bands associated with each signature of the $1/2^+[631]$ band have been observed in ^{237}U, similar to observations in the isotone ^{239}Pu [12].

The strength of octupole correlations is sometimes interpreted in terms of the extent to which the bands of opposite parity interleave in spin forming a single (octupole) rotational sequence. The parity splitting is given by $S(I) = E(I) - [E(I-1)(I+1) + E(I+1)I]/(2I+1)$. When $S(I) = 0$ the bands are perfectly interleaved and this can be interpreted as the rotation of a stable octupole-deformed shape. Two of the best examples of octupole deformation are ^{220}Ra and ^{222}Th in which the limit $S(I) = 0$ is approached over a large spin range as shown in Fig. 4. The ^{239}Pu and ^{240}Pu nuclei approach this limit at $I > 25\hbar$ and this has been interpreted as the stabilisation of octupole deformation at high spin in these nuclei [12]. However, the results for ^{237}U (the isotone of ^{239}Pu) show values of $S(I)$ which saturate at a positive value away from zero, which is indicative of an octupole-vibrational behaviour. It appears that if the plutonium nuclei are indeed examples of stable octupole deformation at high spin then the region in which this happens may be very limited.

5. CONCLUSIONS

Deep-inelastic collisions between ^{238}U and ^{208}Pb nuclei have allowed the study of high-spin states in a range of neutron-rich nuclei near and above ^{208}Pb for the first time. The high-spin states observed in ^{237}U, ^{239}U and ^{240}U have shed new light on the local region of strong octupole correlations first identified around ^{239}Pu. The preliminary results presented for ^{206}Hg, ^{210}Pb and ^{211}Bi demonstrate the prospects for studying high-spin states in nuclei which have been inaccessible until now, but which are of fundamental importance to the nuclear shell model. The ongoing analysis of this complex data-set promises to yield many new results for nuclei in this region

REFERENCES

1   M Pfützner *et al.*, Phys. Lett B 444 (1998) 32.
2   B. Fornal *et al.*, Eur Phys. J A 1 (1998) 355.
3.   M Rejmund *et al.*, Eur Phys. J. A 1 (1998) 261.
4   M Rejmund *et al*, Z. Phys A 359 (1997) 243
5   M Cromaz *et al.*, Nucl Instrum. Meth., in press, M. Cromaz, abstract to this conference.
6   P.J. Daly *et al.*, Z Phys A 288 (1978) 103
7   M. Rejmund *et al*, Eur Phys J A 8 (2000) 161
8.   T.T.S. Kuo and G.H. Herling, NRL Memorandum Report 2258 (Naval Research Laboratory, Washington, 1971).
9.   K H Maier *et al*, Z. Phys A 332 (1989) 263.
10. O Hansen *et al*, Phys Rev C 18 (1978) 1223.
11 D Ward *et al*, Nucl Phys. A600 (1996) 88
12 I Wiedenhover *et al.*, Phys. Rev Lett 83 (1999) 2143.